Forest Research
Technical Report
Vancouver Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

TR-015 Geomorphology February 2002

Using terrain attributes to predict post-logging landslide likelihood on southwestern Vancouver Island

by

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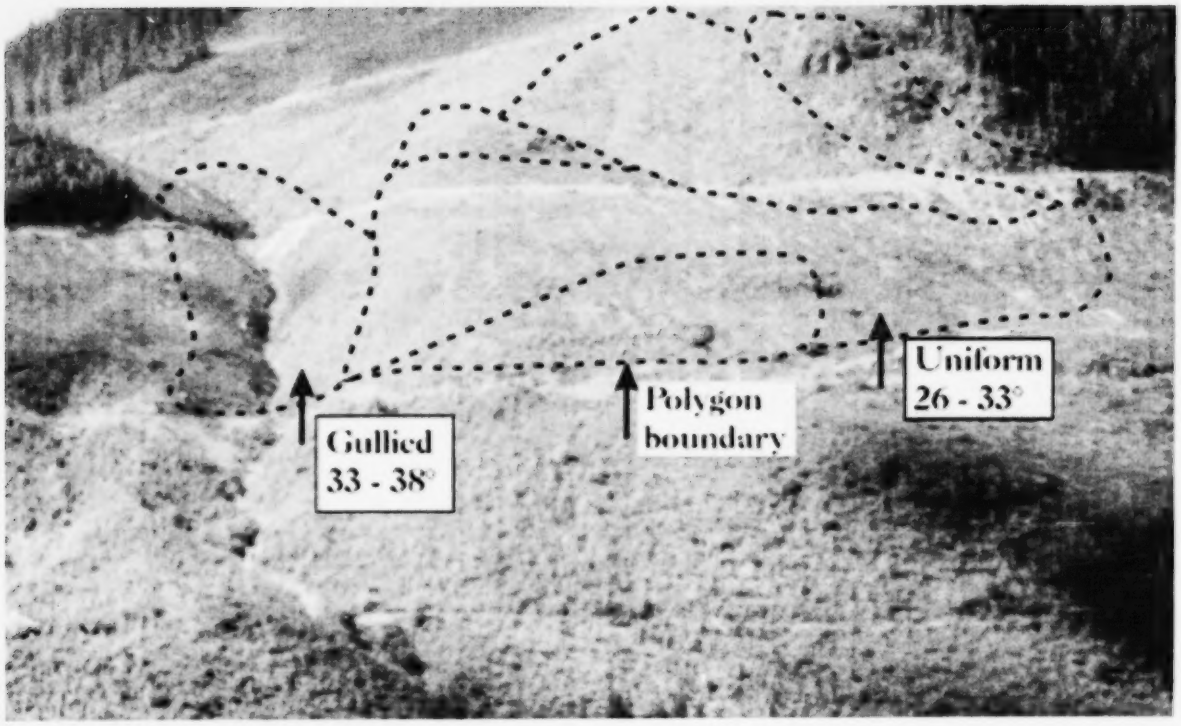

Research Disciplines: Ecology - Geology - Geomorphology - Hydrology - Pedology - Silviculture - Wildlife

Citation:
Rollerson, T., T. Millard and B. Thomson. 2002. Using terrain attributes to predict post-logging landslide likelihood on southwestern Vancouver Island. Res. Sec., Van. For. Reg., B.C. Min. For., Nanaimo, B.C. Tec. Rep. TR-015/2002.

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Cover photo: Typical terrain polygons in southwestern Vancouver Island.

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SUMMARY

Terrain attributes are landscape features that can be used to identify hillslopes susceptible to landslides. For analysis, logged hillslopes were divided into terrain polygons, which are small areas that have a consistent set of terrain attributes such as slope gradient, surficial material type, and slope morphology. Terrain attribute data was systematically collected in the field in conjunction with post-logging landslide data and analysed to identify those terrain attributes that are useful predictors of post-logging landslides. The method provides quantification of landslide likelihood – an important improvement over qualitative landslide likelihood evaluation.

Two measures of landslide likelihood were used in this study. *Landslide presence* is the presence of one or more landslides within a terrain polygon. This study analysed landslide presence using only landslides > 500 m^2 in area, as well as the presence of landslides of any size. *Landslide density* is the average number of landslides in a unit area. In this study, only landslides >500 m^2 were used to determine landslide density. Three post-logging landslide types were evaluated: clearcut landslides, road fill landslides, and road cut landslides. The study used a combination of univariate and multivariate statistical procedures.

Clearcut areas in the Klanawa, Gordon, San Juan, and Caycuse watersheds on southwestern Vancouver Island were studied. A total of 767 terrain polygons was sampled, representing an aggregate area of 3491 ha. The mean polygon area was 4.6 ha, with a standard deviation of 3.7 ha and a range of 0.4 to 27.7 hectares. There were 195 clearcut landslides >500 m^2, 228 road fill landslides >500 m^2, and 47 road cut landslides >500 m^2. A total of 122 (16%) of the 767 terrain polygons in the sample population had *>500 m^2 clearcut landslide presence*. Overall, the average *>500 m^2 landslide density* was 0.06 landslides per hectare (ls/ha). Of the 567 terrain polygons in the study area with roads, 126 (22%) had *>500 m^2 road fill landslide presence*. Thirty-two (6%) of the 567 terrain polygons with roads had *>500 m^2 road cut landslide presence*.

Slope gradient strongly affected all types of landslides, with slopes less than 30° having had much lower landslide likelihood than slopes steeper than 30°. Clearcut landslide density for slopes less than 30° was 0.02 ls/ha, while slopes steeper than 30° had *>500 m^2 clearcut landslide densities* from 0.05 to 0.12 ls/ha. Similarly, less than 15% of samples on slopes <30° had *>500 m^2 road fill landslide presence*, while 21% to 48% of slopes >30° had *>500 m^2 road fill landslide presence*. Road cut landslide presence increased as well with increasing slope gradient. For slopes less than 35°, less than 5% of the samples had *>500 m^2 road cut landslide presence*. For slopes steeper than 35°, from 12 to 15% of the samples had *>500 m^2 road cut landslide presence*.

Gullied terrain had higher landslide likelihoods than other types of slope morphology. Single gullies and dissected terrain (multiple gullies) had *>500 m^2 clearcut landslide densities* of 0.10 – 0.16 ls/ha, compared with other slope morphologies that all had *>500 m^2 clearcut landslide densities* of 0.05 ls/ha or less. Similarly, *>500 m^2 road fill landslide presence* was highest for dissected and single gully terrain (36 and 34%, respectively), compared with other slope morphologies that all had *>500 m^2 road fill landslide presence* less than 20%. Road cut landslides were also highest in dissected and single gully terrain (both had 12% *>500 m^2 road fill landslide presence*), while other slope morphologies had *>500 m^2 road fill landslide presence* of 5% or less. Similar results were found for horizontal curvature, where concave and convex slopes tended to have higher landslide likelihoods. Concave and complex slopes were often gullied slopes. As well, gullies that were deeper had a greater landslide likelihood.

Slopes located on the Leech River bedrock formation had higher clearcut landslide likelihood than other bedrock formations.

The use of terrain attributes is a important part of landslide assessment in Coastal British Columbia. This study provides quantification of landslide likelihood for a valuable forestry area. Since terrain conditions are variable, caution is urged in applying these results to unlogged areas.

KEY WORDS

landslides, terrain, southwestern Vancouver Island.

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ACKNOWLEDGEMENTS

The authors thank Gray Switzer, Mel Zwierink, and Pierre Friele, who ably assisted with the field data collection. Sid Tsang and Eric Lott compiled and edited the data. Reviews were gratefully received from Rick Guthrie, Peter Ott, and Doug VanDine.

1.0 INTRODUCTION

Forestry operations in Coastal British Columbia occur across large tracts of land, often with unstable or potentially unstable terrain broadly distributed across the landscape. Methods of identifying terrain susceptible to landslides are needed that are accurate and yet are rapid enough to be applied to extensive areas.

Terrain attributes are features or characteristics of a specific, relatively uniform portion of a slope, called a terrain polygon. Terrain attribute studies produce statistically derived post-logging landslide likelihoods by identifying significant terrain attributes or groups of terrain attributes. Since identification of these terrain attributes in the field (and to a certain extent on air photos and topographic maps) is usually easy, the method produces assessments of landslide likelihood in a relatively rapid manner.

This study examines logged terrain in southwestern Vancouver Island, British Columbia, an area of extensive forestry operations in steep terrain. This study is one of a series of terrain attribute studies that examines forestry-related landslide likelihood in Coastal British Columbia: Queen Charlotte Islands (Rollerson, 1992); West Coast of Vancouver Island (Rollerson

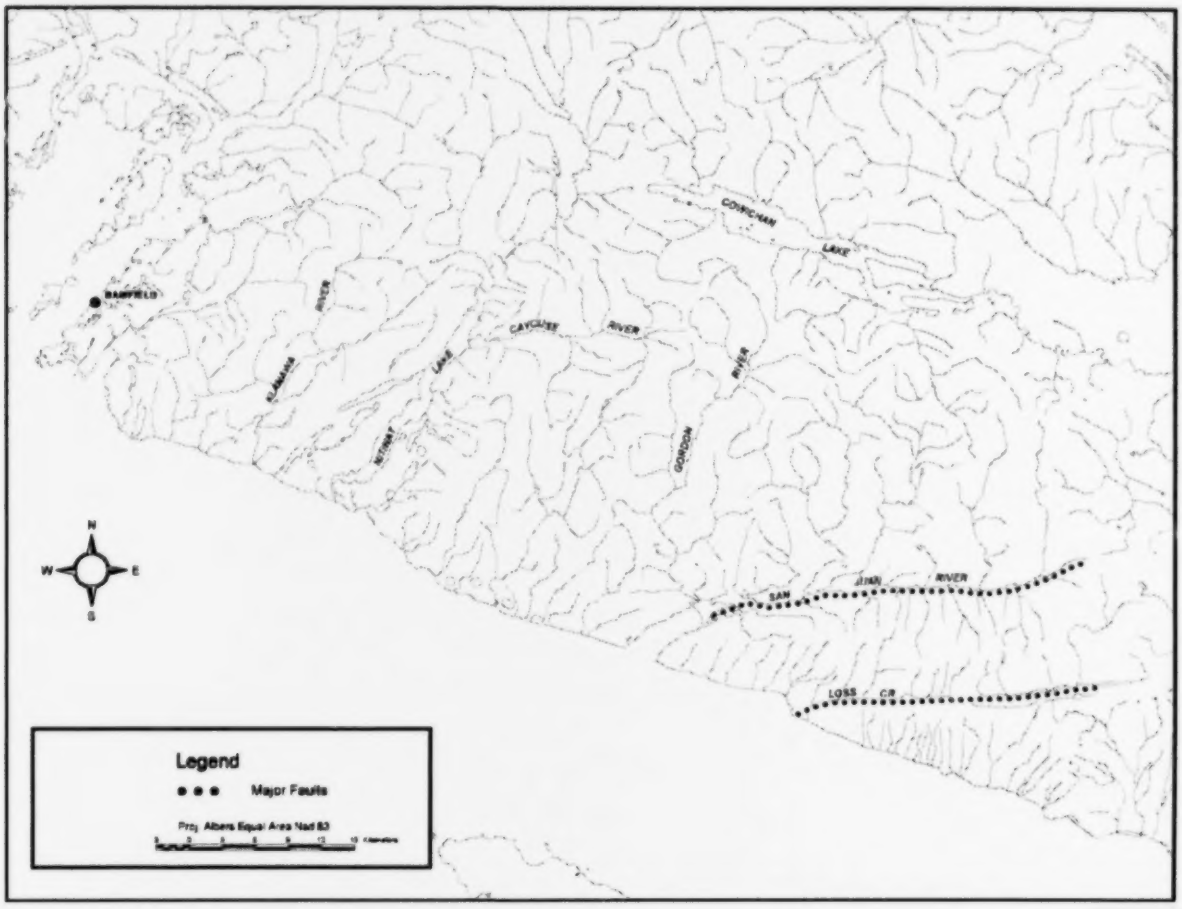


Figure 1. Study area, southwestern Vancouver Island.

et al, 1998); and Coast Mountains (Rollerson et al, 2001).

The objectives of this study are to:

- characterize steep terrain that is susceptible to landslides following logging (clearcutting) and associated road building on southwestern Vancouver Island.
- develop terrain-based stability classifications for southwestern Vancouver Island that estimate the landslide likelihood following logging.

2.0 STUDY AREA

2.1 AREA AND PHYSIOGRAPHY

Data for this study were collected within portions of the Klanawa River and Gordon River watersheds, plus smaller samples from the Caycuse River watershed and a small southern portion of the San Juan River watershed (Figure 1). These areas are located on southwestern Vancouver Island and are typical of the terrain west of Cowichan Lake, from Barkley Sound in the northwest to Loss Creek in the southeast.

The study area lies within the South Vancouver Island Ranges, a physiographic region that is part of the northwest to southeast trending Vancouver Island Range of mountains that forms the core of Vancouver Island (Holland, 1964). The study area is characterized by deeply dissected and rugged terrain. Elevations within the study area range from sea level to 1400 m, with major ridge crests at approximately 1100 m above sea level. Valleys are commonly U-shaped and originate in cirques (Alley and Chatwin, 1979). The valley pattern tends to closely follow major joints, faults, and lineations within the underlying bedrock. Erosion along major lineaments has formed the prominent troughs of Nitinat Lake, Cowichan Lake, San Juan River, and Loss Creek.

2.2 CLIMATE

The study area is vegetated by dense coniferous forest of the Coastal Western Hemlock Biogeoclimatic Zone (Krajina 1969). The average January temperature is 4 to 5 C°; the average July tem-

peratures range between 13 and 18 C° (Krajina, 1969). This zone is the wettest in British Columbia, with annual precipitation varying with location between 1650 and 6650 mm (Krajina, 1969). The weather station at Nitinat Lake Fish Hatchery recorded an average annual precipitation of 4285 mm from 1982 to 1998.

2.3 BEDROCK GEOLOGY

Southwest Vancouver Island is comprised of distinct assemblages of geologic formations, or terranes, that have accreted onto the western margin of North America. Each terrane is composed of one or more geologic formations, and major fault systems separate the terranes. All of the study area north of the San Juan River is composed of the Wrangellia terrane. South of the San Juan River is the Pacific Rim terrane. To the south of the Pacific Rim terrane, and outside of the study area, is the Crescent terrane. The San Juan fault separates Wrangellia from the Pacific Rim terrane, and the Leech River fault separates the Pacific Rim terrane from the Crescent terrane (Yorath and Nasmith, 1995). (Figure 1)

Several bedrock formations are in the Wrangellia terrane. The Island Intrusions are quartz diorite to granite intrusions that commonly underlie the highest portions of the landscape, and extend as a major block in a northwest–southeast trend across the study area. However, the greater part of the study area north of the San Juan Fault zone is underlain by altered volcanic rocks of the Bonanza Group, composed of andesite, dacite, and rhyolite. Exposures of northwest–southeast trending volcanics of the Karmutsen Formation are also found in the northern portion of the area. Minor exposures of northwest–southeast trending Quatsino Formation limestone are also found in association with the Karmutsen and Bonanza suites of rocks. Widespread faulting (Muller 1976) has complicated bedrock geology north of the San Juan Fault, and produced areas where the bedrock is strongly fractured or sheared.

The Pacific Rim terrane is composed of the Leech River formation. The rocks are primarily greywacke, argillite, and schist, with some chert and volcanic rocks (Mueller, 1976).

2.4 SURFICIAL GEOLOGY

Surficial deposits are generally less than 25,000 years old and are related to the Fraser Glaciation (Late Wisconsin) and post-glacial geomorphic processes. Relatively thick (>1m) blankets of till (morainal deposits) are generally restricted to valley bottoms and lower to mid portions of the adjacent slopes. Thin veneers of till are common on upper slopes and ridge tops. Discontinuous veneers of colluvium often overlie till on steeper upper and mid slopes. The till matrix is influenced considerably by local bedrock lithology; finer textured rocks such as volcanics and metamorphics tend to produce a silty till matrix, whereas the coarser textured granitics produce a sandy till matrix.

Glaciofluvial sediments occur in most major valleys, but are more extensive along the southern coastal area (Alley and Chatwin, 1979). Extensive deposits of glaciolacustrine materials are not common, although localized outcrops of silts and clays are found along lower valley side slopes in the Klanawa and San Juan valleys (Figure 1). Post-glacial fluvial sands and gravels are common along river valley bottoms.

3.0 METHODOLOGY

3.1 SAMPLING DESIGN

A number of representative areas were selected within each of the four watersheds in the study area. Within each representative area, all accessible logged areas, ranging in age from six to 15 years following logging, were sampled. The lower age limit was established so that the areas had time to experience a number of large storms after logging, and to give adequate time for root strength loss to occur. The upper age limit was established because increasing tree height and crown closure in plantations older than 15 years tends to mask local terrain features, including small landslides, making collection of accurate data difficult. A number of situations were observed where rapidly growing conifers and alders completely masked the presence of landslides in clearcut areas within 10 to 15 years.

Each selected representative area was mapped at a scale of 1:20,000 using the BC Terrain Classification System (Howes and Kenk, 1997), and 1:15,000 to 1:20,000 scale air photos. Each terrain polygon with a slope gradient greater than 20° was visited in the field. For the sake of efficiency, most terrain polygons with slopes less than 20° were excluded from the study, because they rarely show evidence of post-logging landslides.

It is known that no two terrain mappers map identical terrain polygons for a given landscape, or describe an area in exactly the same manner. Because this study involved several mappers, the terrain mapping approach therefore has introduced some unknown amount of bias or variability. However, bias or variability was limited by providing clear definitions and descriptions of the terrain attributes to be mapped, and by having the mappers work with a mapping coordinator to ensure a consistent approach. During analysis, distinct terrain types were grouped into a smaller set of terrain categories. Such a consolidation of data further reduces the effect of differences in terrain polygon delineation and classification.

Over time, additional sampling within the representative areas will augment the data set derived for this study. Landslide incidence will be updated periodically, usually after major storm events or when new air photos are produced. At any point in time, the data set will slightly under-represent the total number of post-logging landslides that have occurred in the study area.

3.2 DATA COLLECTION

For each terrain polygon, the following terrain attributes were recorded in the field and analysed:

- Slope gradient, recorded as maximum, average, and minimum slope gradients for the polygon;
- Natural landslides >500 m^2 in slope area (absent or present);
- Minor natural landslides <500 m^2 in slope area (absent or present);
- Slope position (four categories);
- Slope morphology (five categories);

- Terrain category (10 groupings of surficial materials);
- Horizontal curvature (four categories);
- Soil drainage (four categories);
- Slope aspect (divided into octants);
- Elevation (divided into five ranges of elevations);
- Bedrock formation (five categories);
- Bedrock lithology (eight categories);
- Bedrock structure (four categories);
- Bedrock competence (three categories);
- Surficial material depth;
- Gully depth.

For each terrain polygon, the following post-logging landslide characteristics were recorded:

- The number of landslides initiated within the clearcut area that were >500 m^2 (slope area for all landslide sizes);
- The number of >500 m^2 landslides initiated within road fills;
- The number of >500 m^2 landslides initiated within or directly above road cuts;
- The presence or absence of one or more landslides <500 m^2 in clearcut areas. Since smaller landslides were difficult to consistently identify, they were not individually enumerated;
- The presence of one or more landslides <500 m^2 associated with road fills;
- The presence of one or more landslides <500 m^2 associated with road cuts.

In addition, signs of potential road fill instability such as tension cracks and fill slope settlement were also recorded.

3.3 DATA ANALYSIS

Two specific measures of post-logging landslide likelihood were used in the analysis: *landslide presence* and *landslide density*.

Landslide presence is the presence of the initiation point of one or more post-logging landslides within a terrain polygon. The analysis reports the percentage of samples with landslides present. Landslide presence was evaluated using four criteria:

1. Only landslides >500 m^2 were used as the dependent variable. This outcome applies to *clearcut landslides*, *road fill landslides* and *road cut landslides*.

2. For clearcut areas, the *presence of landslides of any size* was used as an additional dependent variable.

3. For road fills, the *presence of any signs of instability* was used as a second dependent variable. This measure included landslides of any size, tension cracks, fill slope settlement, or other signs of potential road fill instability.

4. For road cuts, the *presence of landslides of any size* was used as a second dependent variable.

Landslide density is the average number of landslides within a unit area. Landslide density considers only landslides >500 m^2, since smaller landslides were not individually enumerated. For clearcut areas, landslide density was measured as landslides per hectare (ls/ha), based on slope area not planimetric area. Landslide density was not determined for road fill and road cut landslides since road lengths were not recorded.

This approach resulted in seven landslide likelihoods used in the analysis:

- Clearcut landslide likelihood -

1. percentage of polygons with *>500 m^2 clearcut landslide presence;*
2. >500 m^2 clearcut landslide density (ls/ha);
3. percentage of polygons with *any size of clearcut landslide presence.*

- Road fill landslide likelihood -

4. percentage of polygons with *>500 m^2 road fill landslide presence;*
5. percentage of polygons with *any road fill instability presence.*

- Road cut landslide likelihood -

6. percentage of polygons with *>500 m^2 road cut landslide presence;*
7. percentage of polygons with *any road cut landslide presence.*

For each terrain attribute, the seven landslide likelihoods were determined. Chi-square tests were used to test for significant differences in the presence or absence of landslides. The Kruskal-Wallis test was used when testing for significant differences in landslide density. If the statistical test showed significance, then at least some of the categories within a terrain attribute are significantly different from one another, but not necessarily all categories are different. For each test, a significance level of $P = 0.05$ was used.

Analysis of landslide density used weighted samples to produce pseudo-replicates. This reduces the bias that results if samples of unequal size are used to calculate landslide density. Samples were weighted by their area, with a unit area of one hectare used as the nominal sample, and the polygon area rounded to the nearest integer. As an example, a terrain polygon of 3.7 ha would be considered as four samples. The approach is used because it results in a better estimate of mean landslide density.

A limited multivariate analysis was also carried out. Using CHAID (Chi-squared Automatic Interaction Detector), individual terrain polygons that have a similar likelihood of post-logging landslides were grouped into multi-factor terrain categories. CHAID uses a non-parametric, multivariate procedure known as segmentation modeling (Magidson J./SPSS Inc, 1993). The procedure divides a sample population into two or more distinct groups based on the best predictors of a dependent variable. Groups are further subdivided if CHAID identifies additional significant variables. Segments defined by the analysis do not overlap. Both dependent and predictor variables are treated as categorical variables. The procedure merges categories of a predictor variable that are not significantly different at each segmentation level. The analysis produces a tree diagram that identifies the

most significant variables and presents statistics for each separate group or segment of the dependent variable. These categories can form the basis of a terrain stability classification that estimates the likelihood of landslides occurring after clearcut logging and associated road building.

4.0 RESULTS

A total of 767 terrain polygons were sampled in southwestern Vancouver Island, representing an aggregate area of 3491 ha. The mean polygon area was 4.6 ha, with a standard deviation of 3.7 ha and a range of 0.4 to 27.7 hectares. The median polygon size was 3.5 ha. There were 195 clearcut landslides >500 m^2, 228 road fill landslides >500 m^2, and 47 road cut landslides >500 m^2.

The following sections outline the relationships identified between various terrain attributes and clearcut, road fill and road cut related landslide activity. The reader is reminded that the slopes studied are generally equal to or steeper than 20°, a factor that has some bearing on the relationships described below. For example, slope position rarely if ever shows a significant relationship to landslide activity. This result is an artifact of the exclusion from the sample population of the gentle slopes often found along toe slopes and ridge crests.

Landslide presence provides a general estimate of the probability of landslide likelihood within a given attribute category; however, it is dependent on polygon size. Polygons with landslides were significantly larger than polygons without landslides (an average of 5.3 ha compared with 4.4 ha).

4.1 UNIVARIATE TERRAIN ATTRIBUTE ANALYSIS

Univariate analysis of the terrain attribute data is used to describe general results and to draw general conclusions. However, there may be confounding factors affecting the results. As an example, steeper slopes may be associated with a specific terrain type. If the specific terrain type has a high landslide likelihood, it may actually be a result of steeper slopes, not terrain type. In addition, since the study sampled the available terrain units, there may be some variable categories that have a limited number of samples. Results for categories that have limited sample numbers should be used cautiously.

4.1.1 CLEARCUT LANDSLIDES (TABLES 1 AND 2)

A total of 122 (16%) of the 767 terrain polygons in the sample population have *>500 m^2 clearcut landslide presence*. Overall, the average *>500 m^2 landslide density* is 0.06 ls/ha. If *any size of clearcut landslide presence* is considered, then 280 (36%) of the terrain polygons experienced one or more clearcut landslides, although some were quite small.

There are significant differences in clearcut landslide activity for several of the terrain attributes, regardless of whether *>500 m^2 clearcut landslide presence*, *>500 m^2 landslide density*, or *any size of clearcut landslide presence* is considered as the post-logging landslide likelihood measure. Differences in slope gradient, slope morphology, horizontal curvature, and gully depth are strongly related to clearcut landslide likelihood, as indicated by significance levels in Table 1.

Table 1. Comparison of terrain attributes with clearcut landslide likelihood.

Terrain Attribute	P-value		
	>500 m^2 clearcut landslide presence[1]	*>500 m^2 clearcut landslide density*[2]	*Any clearcut landslide presence*[1]
Slope gradient	<0.001	<0.001	<0.001
Natural landslides >500 m^2	ns	ns	ns
Minor natural landslides	ns	0.002	ns
Slope position	ns	<0.001	0.016
Slope morphology	<0.001	<0.001	<0.001
Horizontal curvature	<0.001	<0.001	<0.001
Soil drainage	ns	<0.001	<0.001
Slope aspect	ns	0.000	ns
Elevation	ns	0.010	ns
Terrain category	ns	<0.001	ns
Bedrock formation	<0.001	<0.001	ns
Bedrock lithology	<0.001	<0.001	ns
Bedrock structure	ns	<0.001	0.046
Bedrock competence	ns	ns	ns
Surficial material depth	ns	<0.001	0.030
Gully depth	0.001	<0.001	<0.001

(1) Chi-square test
(2) Kruskal-Wallis test
(ns: not significant)

Slopes with a gradient less than 30° had average *>500 m^2 landslide densities* of 0.02 ls/ha (Table 2). Slopes with a gradient of 31-35° had *>500 m^2 landslide density* of 0.12 ls/ha, and slopes steeper than 40° had 0.09 ls/ha. Slopes steeper than 40° had a greater proportion of terrain types with rock outcrops (78% of slopes >40° compared with 18% for the entire sample), and this is likely the reason why the steepest slopes did not have the highest landslide likelihood.

Slopes with gullies (either single gullies or dissected morphology) had *>500 m^2 landslide densities of 0.10 – 0.16* ls/ha, whereas other slope morphologies had 0.05 ls/ha or less. As gully depth increased, *>500 m^2 landslide density* increased from 0.04 ls/ha to 0.18 ls/ha (Table 2). Concave slopes were strongly associated with gullies and had higher landslide likelihoods compared with other horizontal curvatures.

Table 1 indicates that slope position, soil drainage, bedrock formation, bedrock lithology, bedrock structure, and surficial material depth show weaker associations with landslide activity. Lower slope polygons had 0.13 ls/ha, compared with 0.04–0.05 ls/ha for mid and upper slopes. Rapidly drained soils had somewhat higher landslide likelihoods, probably a result of rapidly drained soils being on steeper slopes. Of the bedrock formations, the Leech River formation had the highest *>500 m^2 landslide density* of 0.21 ls/ha, the Quatsino formation had 0.17 ls/ha, the Bonanza formation had 0.09 ls/ha, and the other two bedrock formations had 0.04 ls/ha or less. The result for the Quatsino formation should be considered tentative since there were only 14 samples. All of the Leech River samples had phyllite lithology. Sheared and massive bedrock had higher landslide likelihoods than fractured bedrock structures. Slopes with surficial material depths greater than 2.5 m showed the greatest landslide likelihoods.

Table 2. Terrain attributes - clearcut landslides summary statistics.

Terrain Attribute	Code	n	>500 m^2 clearcut landslide presence (%)	Average >500 m^2 clearcut landslide density (#/ha)	Any clearcut landslide presence (%)
Slope gradient (°)					
≤20	1	4	-	-	-
21 – 25	2	152	6	0.02	16
26 – 30	3	159	9	0.02	33
31 – 35	4	250	14	0.05	37
36 – 40	5	156	32	0.12	55
>40	6	46	24	0.09	52
Natural landslides					
absent	0	760	16	0.06	36
present	1	7	14	0.03	86
Minor natural landslides					
absent	0	761	16	0.06	36
present	1	6	0	0.00	36
Slope position					
apex	1	4	-	-	-
upper slope	2	179	13	0.04	31
mid slope	3	533	16	0.05	37
lower slope	4	51	22	0.13	55
Slope morphology					
uniform	1	483	14	0.05	27
benchy	2	25	8	0.02	12
dissected (>1 gully)	3	85	28	0.10	73
irregular	5	86	8	0.01	19
single gullies	6	88	27	0.16	74
Terrain category					
Morainal blankets/veneers	1	160	17	0.07	33
Morainal veneers	2	131	9	0.03	30
Colluvial blankets/veneers	3	28	11	0.03	46
Colluvial veneers	4	90	19	0.06	34
Glaciofluvial & moraine/F[G]	5	9	33	0.18	44
Rock & rock/colluvial	6	28	4	0.01	32
Morainal+colluvial blankets	7	16	25	0.12	31
Morainal+colluvial	8	126	15	0.07	37
Morainal+rock	9	77	17	0.07	36
Colluvial/rock	10	102	22	0.07	50
Horizontal curvature					
Concave	1	247	28	0.11	64
Convex	2	141	12	0.05	19
Straight	3	338	9	0.02	24
Complex	4	41	15	0.03	39
Soil drainage					
Rapidly	1	154	21	0.07	51
Well	2	555	15	0.05	34
Moderately well	3	57	15	0.05	26
Imperfectly	4	1	-	-	-
Slope aspect					
NNE	1	84	24	0.08	40
ENE	2	55	15	0.06	42
ESE	3	108	13	0.05	40
SSE	4	112	12	0.03	28
SSW	5	100	9	0.03	29
WSW	6	83	15	0.03	40
WNW	7	106	19	0.06	43
NNW	8	118	21	0.10	34
Elevation (m)					
≤200	1	58	17	0.10	41
201 – 400	2	188	14	0.04	38
401 – 600	3	309	17	0.06	37
601 – 800	4	181	16	0.06	32
801 – 1000	5	31	16	0.08	35
Bedrock formation					
Island Intrusions	1	573	13	0.04	35
Bonanza	2	76	20	0.09	40
Karmutsen	3	26	11	0.02	27
Quatsino	4	14	14	0.17	29
Leech River	6	78	39	0.21	50
Bedrock lithology					
granite	2	114	15	0.03	33
granodiorite	4	92	11	0.03	34
quartz diorite	5	175	13	0.04	38
rhyodacite lava	13	21	9	0.02	48
andesite	15	8	25	0.14	50
basalt	17	44	14	0.04	34
phyllite	22	58	40	0.21	52
limestone	58	12	8	0.04	17
Bedrock structure					
massive	1	36	17	0.06	28
fractured	2	256	11	0.03	35
sheared	3	40	23	0.06	50
bedded	4	2	-	-	-
Bedrock competence					
high	1	192	11	0.04	34
moderate	2	32	16	0.03	37
low	3	6	33	0.05	33
Surficial material depth (m)					
≤0.5	1	130	16	0.04	37
0.6 – 1.0	2	217	16	0.05	33
1.1 – 1.5	3	158	14	0.04	30
1.6 – 2.0	4	126	17	0.05	39
2.1 – 2.5	5	18	6	0.01	22
2.6 – 3.0	6	37	29	0.09	42
>3.0	7	81	21	0.16	51
Gully depth (m)					
0 – ≤3	1	68	13	0.04	44
3.1 – 6	2	67	21	0.06	72
6.1 – 9	3	38	29	0.14	66
>9	4	56	43	0.18	87

Note: proportion symbols: / indicates dominant/subdominant; + indicates either component may be dominant or it may be equivalent.

4.1.2 ROAD FILL LANDSLIDES (TABLES 3 AND 4)

Of the 567 terrain polygons in the study area with roads, 126 (22%) had *>500 m^2 road fill landslide presence*. If *any road fill instability presence* is considered then 290 (51%) of the terrain polygons had unstable road sections.

Road fill landslides tend to be significantly associated with slope gradient, slope morphology, horizontal curvature, soil drainage, slope aspect, terrain category, and surficial material depth, regardless of the landslide likelihood measure tested (Table 3).

There was an increasing incidence of road fill landslide activity as slope gradient increased. Four percent of the polygons with <26° slope gradient had *>500 m^2 road fill landslide presence* (Table 4). In contrast, 48% of the samples with slope gradients between 35 and 40° had *>500 m^2 road fill landslide presence*. Thirty-six percent of the steepest slopes (>40°) had *>500 m^2 road fill landslide presence* – a lower percentage than polygons on slopes

of 35 to 40°, and perhaps a reflection of an increased use of full bench construction techniques on these very steep slopes.

Slopes with gullied morphology (dissected and single gullies) had a higher incidence of road fill landslides than other slope morphologies (Table 4). Concave and complex horizontal curvature had *>500 m³ road fill landslide presence* in 30% and 36% of the samples, respectively. In contrast, both convex and straight slopes had *>500 m³ road fill landslide presence* in 17% of the samples.

Rapidly drained soils had the highest landslide likelihood compared with well and moderately well drained soils. The increase in road fill landslides as soil drainage improved from moderately well drained to rapidly drained may be related to slope gradient, because rapidly drained soils tend to occur on steep slopes. Average slope gradient for rapidly drained, well drained, and moderately well drained slopes were 37°, 31°, and 26°, respectively.

Table 3. Comparison of terrain attributes with road fill landslide likelihood.

Terrain Attribute	P-Value (Chi-Square)	
	>500 m³ road fill landslide presence	*Any road fill instability*
Slope gradient	<0.001	<0.001
Slope position	ns	ns
Slope morphology	0.002	<0.001
Horizontal curvature	0.002	<0.001
Soil drainage	<0.001	0.021
Slope aspect	0.020	0.012
Elevation	ns	<0.001
Terrain category	<0.001	<0.001
Bedrock formation	ns	ns
Bedrock lithology	ns	ns
Bedrock structure	0.007	ns
Bedrock competence	ns	ns
Surficial material depth	<0.001	<0.001
Gully depth	ns	0.029

Table 4. Terrain attributes – road fill landslides summary statistics.

Terrain Attribute	Code	n	*>500 m³ road fill landslide presence (%)*	*Any road fill instability presence (%)*
Slope gradient (°)				
≤20	1	3	-	-
21 – 25	2	117	4	21
26 – 30	3	117	15	44
31 – 35	4	189	21	56
36 – 40	5	113	48	80
>40	6	28	36	64
Slope position				
apex	1	3	-	-
upper slope	2	129	23	46
mid slope	3	405	22	52
lower slope	4	30	20	57
Slope morphology				
uniform	1	362	20	48
benchy	2	21	9	48
dissected (>1 gully)	3	66	36	68
irregular	5	59	15	32
single gullies	6	59	34	70
Terrain category				
Morainal blankets/veneers	1	114	14	37
Morainal veneers	2	93	13	40
Colluvial blankets/veneers	3	22	36	73
Colluvial veneers	4	71	30	63
Glaciofluvial & moraine/F[G]	5	5	-	-
Rock & rock/colluvial	6	15	33	53
Morainal+colluvial blankets	7	11	36	91
Morainal+colluvial	8	114	20	58
Morainal+rock	9	50	16	30
Colluvial/rock	10	72	36	65
Horizontal curvature				
concave	1	174	30	63
convex	2	102	17	34
straight	3	258	17	48
complex	4	33	36	67
Soil drainage				
rapidly	1	111	36	61
well	2	413	20	50
moderately well	3	42	9	36
imperfectly	4	1	-	-
Slope aspect				
NNE	1	60	23	58
ENE	2	39	26	43
ESE	3	75	35	64
SSE	4	82	27	54
SSW	5	77	26	60
WSW	6	63	16	44
WNW	7	86	14	48
NNW	8	84	14	37

Terrain Attribute	Code	n	*>500 m³ road fill landslide presence (%)*	*Any road fill instability presence (%)*
Elevation (m)				
≤200	1	31	16	35
201 – 400	2	141	17	41
401 – 600	3	226	26	59
601 – 800	4	146	21	47
801 – 1000	5	23	39	78
Bedrock formation				
Island Intrusions	1	426	24	53
Bonanza	2	54	19	44
Karmutsen	3	21	9	57
Quatsino	4	12	33	42
Leech River	6	54	15	41
Bedrock lithology				
granite	2	95	28	54
granodiorite	4	77	21	51
quartz diorite	5	120	30	64
rhyodacite lava	13	14	7	43
andesite	15	7	29	43
basalt	17	37	16	54
phyllite	22	41	19	46
limestone	58	10	30	40
Bedrock structure				
massive	1	28	36	71
fractured	2	194	20	51
sheared	3	34	41	82
bedded	4	1	-	-
Bedrock competence				
high	1	134	18	55
moderate	2	28	18	64
low	3	6	-	-
Surficial material depth (m)				
≤0.5	1	103	34	61
0.6 – 1.0	2	156	22	60
1.1 – 1.5	3	116	9	34
1.6 – 2.0	4	96	21	45
2.1 – 2.5	5	15	7	40
2.6 – 3.0	6	27	22	7
>3.0	7	52	33	64
Gully depth (m)				
0 – ≤3	1	53	19	47
3.1 – 6	2	54	39	70
6.1 – 9	3	21	29	67
>9	4	35	31	74

ns: not significant

proportion symbols: / indicates dominant/subdominant;

+ indicates either component may be dominant or it may be equivalent.

Slopes facing towards the east and south appear to have had greater landslide presence than slopes facing from southwest to northwest. This is in contrast to clearcut landslides, where southerly facing slopes appeared to have had the lowest landslide likelihoods. The contrast suggests that slope aspect is not a useful result.

Although the Chi-square test indicated surficial material depth was a significant factor in landslide likelihood (Table 3), there was no trend in landslide likelihood as surficial material depth increased (Table 4), and therefore the statistical result is likely spurious.

4.1.3 ROAD CUT LANDSLIDES (TABLES 5 AND 6)

Thirty-two (6%) of the 567 terrain polygons with roads had *>500 m³ road cut landslide presence*. If *any road cut landslide presence* is considered then 228 (40%) of the terrain polygons experienced landslides.

Road cut landslide likelihoods were significantly related to slope

Table 5. Comparison of terrain attributes with road cut landslide likelihood.

Terrain Attribute	P-value (Chi-Square)	
	>500m³ road cut landslide presence	*Any road cut landslide presence*
Slope gradient	0.001	<0.001
Slope position	ns	ns
Slope morphology	0.012	0.031
Horizontal curvature	<0.001	0.001
Soil drainage	ns	ns
Slope aspect	ns	0.031
Elevation	ns	ns
Terrain category	0.002	0.037
Bedrock formation	0.030	0.010
Bedrock lithology	ns	ns
Bedrock structure	0.049	ns
Bedrock competence	ns	ns
Surficial material depth	ns	ns
Gully depth	<0.001	0.017

Table 6. Terrain attributes - road cut landslides summary statistics.

Terrain Attribute	Code	n	*>500 m³ road cut landslide presence (%)*	*Any road cut landslide presence (%)*
Slope gradient (°)				
≤20	1	3	-	-
21 – 25	2	117	1	21
26 – 30	3	117	3	41
31 – 35	4	189	5	44
36 – 40	5	113	12	53
>40	6	28	14	46
Slope position				
apex	1	3	-	-
upper slope	2	129	3	35
mid slope	3	405	6	42
lower slope	4	30	7	40
Slope morphology				
uniform	1	362	4	38
benchy	2	21	0	38
dissected	3	66	12	55
irregular	5	59	5	29
single gullies	6	59	12	47
Terrain category				
Morainal blankets/veneers	1	114	4	35
Morainal veneers	2	93	1	35
Colluvial blankets/veneers	3	22	0	36
Colluvial veneers	4	71	7	38
Glaciofluvial & moraine/F^{0}	5	5	-	-
Rock & rock/colluvial	6	15	20	27
Morainal+colluvial blankets	7	11	0	18
Morainal+colluvial	8	114	4	52
Morainal+rock	9	50	8	50
Colluvial/rock	10	72	10	36
Horizontal curvature				
concave	1	174	12	50
convex	2	102	2	30
straight	3	258	2	36
complex	4	33	12	54
Soil drainage				
rapidly	1	111	7	39
well	2	413	6	41
moderately well	3	42	0	38
imperfectly	4	1	-	-
Slope aspect				
NNE	1	60	12	47
ENE	2	39	5	44
ESE	3	75	4	33
SSE	4	82	4	35
SSW	5	77	5	33
WSW	6	63	5	46
WNW	7	86	5	55
NNW	8	84	7	33

Terrain Attribute	Code	n	*>500 m³ road cut landslide presence (%)*	*Any road cut landslide presence (%)*
Elevation (m)				
≤200	1	31	3	35
201 – 400	2	141	8	38
401 – 600	3	226	7	47
601 – 800	4	146	4	35
801 – 1000	5	23	0	26
Bedrock formation				
Island Intrusions	1	426	5	41
Bonanza	2	54	4	26
Karmutsen	3	21	0	71
Quatsino	4	12	8	42
Leech River	6	54	15	39
Bedrock lithology				
granite	2	95	7	44
granodiorite	4	77	4	42
quartz diorite	5	120	7	51
rhyodacite lava	13	14	0	57
andesite	15	7	0	43
basalt	17	37	0	27
phyllite	22	41	17	44
limestone	58	10	0	40
Bedrock structure				
massive	1	28	4	61
fractured	2	194	5	52
sheared	3	34	18	53
bedded	4	1	-	-
Bedrock competence				
high	1	134	7	63
moderate	2	28	4	79
low	3	6	-	33
Surficial material depth (m)				
≤0.5	1	103	10	38
0.6 – 1.0	2	156	5	44
1.1 – 1.5	3	117	2	44
1.6 – 2.0	4	95	4	27
2.1 – 2.5	5	15	0	0
2.6 – 3.0	6	29	0	48
>3.0	7	30	17	43
Gully depth (m)				
0 – ≤3	1	53	2	40
3.1 – 6	2	55	4	44
6.1 – 9	3	20	15	65
>9	4	35	31	57

ns: not significant

proportion symbols: / indicates dominant/subdominant;

+ indicates either component may be dominant or it may be equivalent.

gradient, slope morphology, terrain category, horizontal curvature, bedrock formation, and gully depth (Table 5).

As with road fill landslide likelihoods, there was a general increase in road cut landslide likelihoods as slope gradient increased. Although *any road cut landslide presence* was less for the steepest slopes compared to slopes from 35 – 40° (as it was for road fill landslide likelihoods), the *>500 m² road cut landslide presence* was highest for the steepest slopes (Table 6).

Both single gullies and dissected slopes had 12% of the samples with *>500 m² road fill landslide presence*, and about 50% of the gullied samples had *any road cut landslide presence* – the highest road cut landslide likelihoods of any of the slope morphologies. As gully depth increases, so too did road cut landslide likelihood.

Although in Table 5 the Chi-Square tests show that terrain category is a significant variable, examination of the landslide likelihoods in Table 6 shows no clear pattern. The highest *>500 m² road fill landslide presence* for a terrain category was 20% of polygons that had rock or rock/colluvial terrain, however the *any road cut landslide presence* for rock or rock/colluvial terrain showed the second lowest likelihood, and there were only 15 such samples. Only the moraine+rock terrain category showed both a high *>500 m² road fill landslide presence* (8%) and a high *any road cut landslide presence* (50%).

Concave and complex slopes had higher road cut landslide likelihoods compared with convex and straight slopes. This result was consistent for clearcut landslides, road fill landslides, and road cut landslides. In both concave and complex slopes, topography concentrates subsurface drainage, and this was likely the cause of the increased numbers of landslides.

Table 5 indicates that there were weak relationships between road cut landslide likelihoods and the various bedrock attributes. Sheared bedrock samples showed a higher *>500 m² road fill landslide presence* (18%) than massive or fractured bedrock samples (4 and 5%, respectively). However sheared bedrock samples did not show a higher *any road cut landslide presence* (53%) than massive or fractured bedrock samples (61 and 52%, respectively).

4.2 MULTIVARIATE TERRAIN ATTRIBUTE ANALYSIS

4.2.1 CLEARCUT LANDSLIDES (FIGURES 2 AND 3)

Figure 2 presents the results of a CHAID multivariate analysis of *>500 m² clearcut landslide presence*. In Figure 2, the topmost line shows the dependent variable being analysed – in this case *>500 m² clearcut landslide presence*. Within the first box "Category 0" shows that 84% of the samples did not have any landslides, and "Category 1" shows that 16% of samples did have landslides. CHAID selected maximum slope angle (gradient) as the most significant predictor of *>500 m² clearcut landslide presence*, with a P-value significance of 0.0000 (and a Chi-square value of 54 and 2 degrees of freedom). CHAID split the samples into three groups: slopes from 21 - 33° (5% *>500 m² clearcut landslide presence*), slopes from >33 - 40° (15% *>500 m² clearcut landslide presence*), and slopes >40° (31% *>500 m² clearcut landslide presence*).

Further divisions of each group occurred, with bedrock formation and aspect the next most significant divisions. For rock

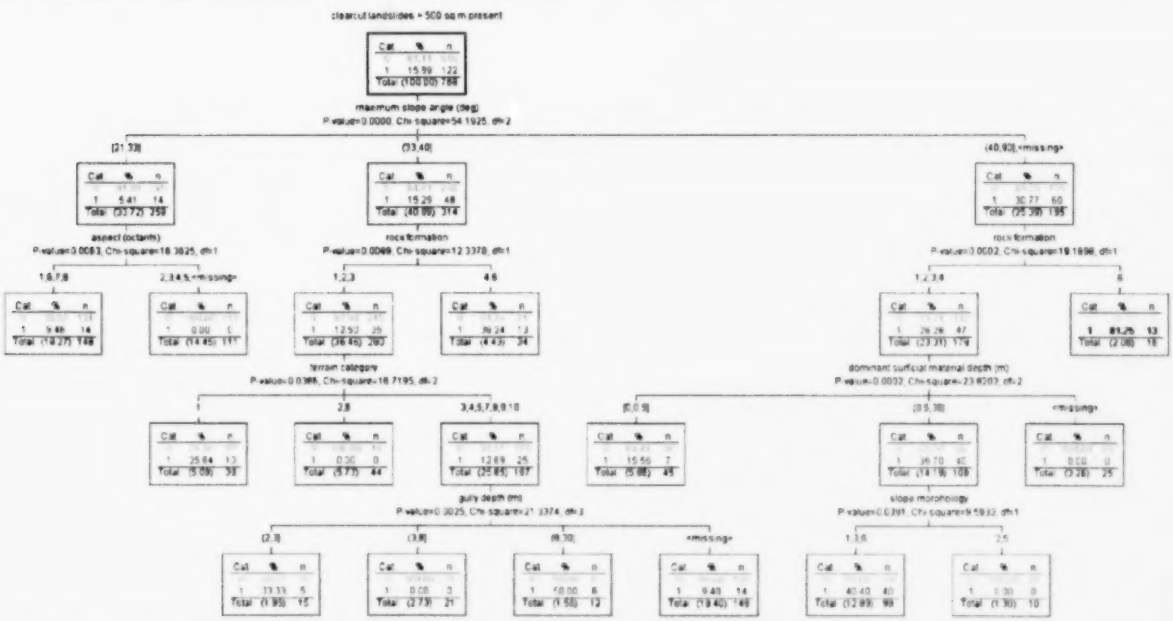


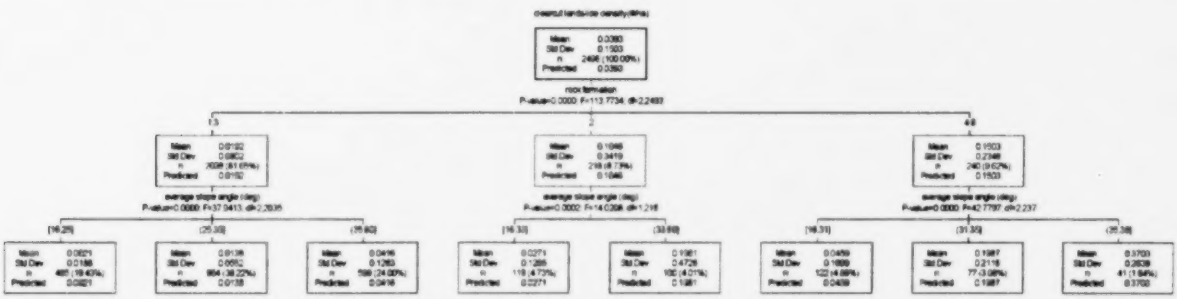
Figure 2. CHAID tree for ***>500 m² clearcut landslide presence*** for southwestern Vancouver Island.

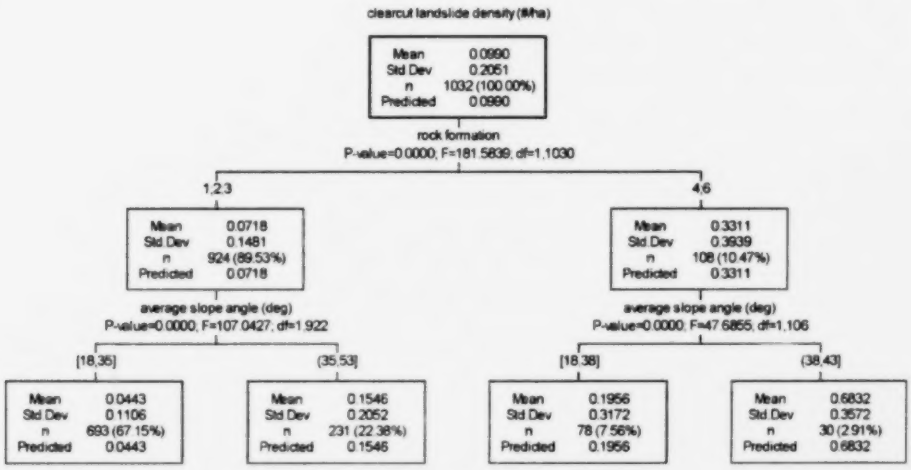
formation, CHAID separated the Leech River formation (code 6 in Figure 2, as listed in Table 2) from the Island Intrusions, Bonanza, and Karmutsen formations. The Quatsino formation (code 4) was grouped with the Leech River formation for slopes 33 - 40°, but was grouped with the Island Intrusions, Bonanza, and Karmutsen formations for slopes steeper than 40°. The difference in the grouping suggests the analysis was affected by the smaller sample sizes within the subdivisions, and that the Quatsino formation may be intermediate in its landslide likelihood. CHAID selected aspect as a significant variable for slopes less than 33°, with northerly slope aspects having a greater landslide likelihood than southerly slope aspects. As noted before, clearcut and road fill landslide results were contrary when considering aspect, and it is likely that this result is an artifact of the smaller sample sub-population.

The CHAID analysis produced additional divisions of the samples based on terrain category, dominant surficial material depth, gully depth, and slope morphology. Under "gully depth", "missing" indicates non-gullied terrain. The final CHAID branches have *>500 m² clearcut landslide presence* ranging from 0% landslide presence to 81% landslide presence.

Figures 3a and 3b present the results of a CHAID multivariate analysis of >500 m2 clearcut landslide density. Variables identified in this analysis were not automatically selected by CHAID. Instead, variables were selected manually for both significance and consistency. The resulting CHAID trees uses only three variables to determine landslide density.

The initial split was based on the presence of gullies – a combination of dissected and single gully morphologies. Figure 3a shows the results for non-gullie' slopes, and Figure 3b shows the results for gullied slopes. Non-gullied slopes had an average of 0.039 ls/ha (the top box of Figure 3a), whereas gullied slopes had an average of 0.099 ls/ha (the top box of Figure 3b). The top box in Figure 3a also shows the standard deviation is 0.15 and the total weighted sample size is 2496. (Ignore the predicted values.) In both Figure 3a and Figure 3b, bedrock formation is used as the next split, with the Quatsino and Leech River formations grouped together and the Island Intrusions and the Karmutsen grouped together. In Figure 3a the Bonanza Group





Figures 3a (top) and 3b. CHAID trees for ***>500 m² clearcut landslide density*** for southwestern Vancouver Island, for non-gullied slopes (3a) and gullied slopes (3b).

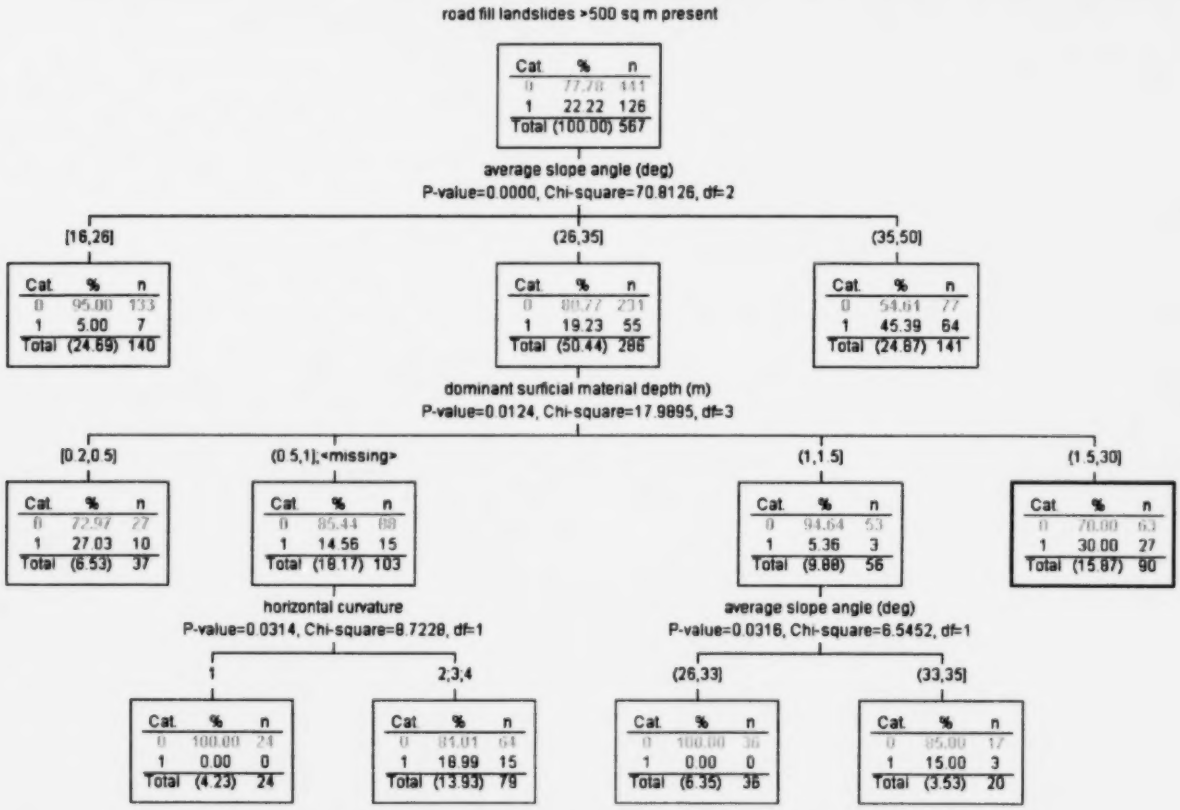


Figure 4. CHAID tree for ***>500 m² road fill landslide presence*** for southwestern Vancouver Island.

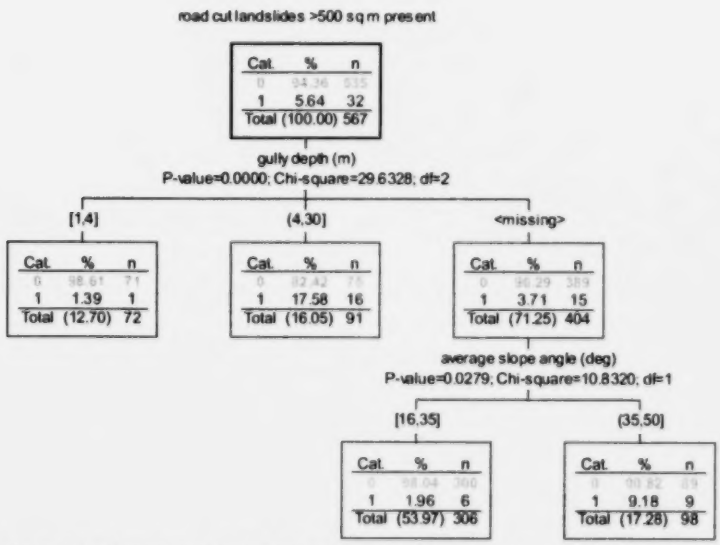


Figure 5. CHAID tree for ***>500 m² road cut landslide presence*** for southwestern Vancouver Island.

is separate, whereas in Figure 3b the Bonanza Group is combined with the Island Intrusions and the Karmutsen formation. Final splits in Figures 3a and 3b all used average slope gradient, with most splits at about 26°, and 33° or 35°. Landslide densities ranged from 0.002 - 0.68 ls/ha. Although the Quatsino formation was grouped in both cases with the Leech River formation, caution is urged given the low sample numbers for the Quatsino formation.

4.2.2 ROAD FILL LANDSLIDES (FIGURE 4)

Figure 4 shows the CHAID analysis for *>500 m² road fill landslide presence*. CHAID grouped polygons initially on average polygon slope gradient. Five percent of polygons with a slope gradient of <26° had *>500 m² road fill landslides*, 19% of polygons with slopes from 26 to 35° had *>500 m² road fill landslides*, and 45% of polygons with slopes >35° had *>500 m² road fill landslides*.

CHAID used surficial material depth to subdivide the polygons with slope gradients from 26°to 35°. The percentage of polygons with landslides decreased as surficial material depth increased to 1.5m, but then increased for the deeper surficial materials. Slope curvature and slope gradient were used to further subdivide some groupings of material depth. The analysis resulted in *>500 m² road fill landslide presence* ranging from 0% to 45%.

4.2.3 ROAD CUT LANDSLIDES (FIGURE 5)

Figure 5 shows the CHAID analysis for *>500 m² road cut landslide presence*. CHAID identified only two variables that were significant for *>500 m² road cut landslide presence* – gully depth and slope gradient. Deeper gullies were more likely to have *>500 m² road cut landslide presence*. Eighteen percent of gullies deeper than 4m had road cut landslides, compared with just 1% of gullies <4m in depth. On open slopes (classified as "missing" in Figure 5) the incidence of *>500 m² road cut landslide presence* averaged 4%, and increased to 9% if the slope gradient was >35°.

5.0 DISCUSSION AND CONCLUSION

There are a number of important terrain attributes that are consistent indicators of landslide likelihood (Table 7). There is a strong increase in landslide likelihood as slope gradient increases, with the exception of clearcut landslides in the steepest terrain, where rocky slopes dominate. Road fill and road cut landslide likelihoods show similar increases. Among the most important terrain attributes is the presence of gullies. Slopes with gullied slope morphology (single gullies and dissected) rank as the highest hazard morphologies for clearcut, road fill, and road cut landslides. Landslide likelihood tends to increase with increasing gully depth. Slopes with concave or complex horizontal curvature are also associated with increased landslide likelihood.

In addition to the terrain attributes listed above, clearcut landslide likelihood in this study is strongly affected by bedrock type. In particular, the Leech River formation showed elevated landslide likelihood.

The CHAID multivariate analysis selected terrain attributes that are almost always identified as significant terrain attributes in the univariate analyses. Slope gradient, rock formation, the presence of gullies or gully depth, and horizontal curvature are com-

Table 7. Summary of important terrain attributes

Type of landslide	Univariate analysis	Multivariate analysis
Clearcut	Significant terrain attributes: • slope gradient • slopes with gullies • slopes with concave or complex horizontal curvature • gully depth Less significant terrain attributes: • Leech River and Bonanza bedrock formation • bedrock structure	Most useful terrain attributes from *landslide presence*: • slope gradient • bedrock formation • terrain category • surficial depth • gully depth • slope morphology Most useful terrain attributes from *landslide density*: • presence of gullies • bedrock formation • slope gradient
Road fill	Significant terrain attributes: • slope gradient • slopes with gullies • slopes with concave or complex horizontal curvature	Most useful terrain attributes from *landslide presence*: • slope gradient • dominant surficial material depth • horizontal curvature
Road cut	Significant terrain attributes: • slope gradient • slopes with gullies • horizontal curvature • bedrock formation Less significant terrain attributes: • sheared bedrock structure	Most useful terrain attributes from *landslide presence*: • gully depth • slope gradient

mon terrain attributes selected by CHAID for landslide likelihood. CHAID selects slope gradient as the most significant terrain attribute for both *>500 m² clearcut landslide presence* (Figure 2) and *>500 m² road fill landslide presence* (Figure 4). As CHAID divides the sample population into smaller groups, it becomes sensitive to the smaller sample sizes it analyses. As a result, the splits on the lowest branches of the CHAID tree should be viewed with some caution.

The assessment of all signs of instability associated with road fills may provide a better long-term estimate of the likelihood of larger road fill landslides. Due to the nature of some earlier logging road construction – such as fills supported by slowly deteriorating buried logs and stumps – more large landslides are likely to occur as these roads grow older.

Overall landslide likelihood results from this study show that southwest Vancouver Island has a similar post-logging landslide likelihood to other areas of the west coast of Vancouver Island (Rollerson et al, 1998). Seventeen percent of the samples from the west coast of Vancouver Island study (Rollerson et al, 1998) had *clearcut >500 m² landslide presence*, while in southwestern Vancouver Island, 16% of the samples had *clearcut >500 m² landslide presence*. Clearcut landslides were more likely in the Queen Charlotte Islands, where 30% of the samples with slopes steeper than 20° had had *clearcut >500 m² landslide presence* (Rollerson, 1992). However, *clearcut >500 m² landslide presence* was much lower in the Coast Mountains, where less than 3% of the samples had landslides (Rollerson et al, 2001).

The results from this study are similar to results from other locations within this study series. Slopes steeper than 30° always have higher landslide likelihoods than slopes <30°. As in this study, gullies almost always rank as the most unstable slope morphology in other Coastal B.C. terrain attribute studies (Table 8).

Road fill landslide likelihood in southwestern Vancouver Island was elevated compared with other areas in Coastal British Columbia. Fifteen percent of the samples in the Queen Charlotte Islands had road fill landslides *>500 m² road fill landslide presence*, while less than 4% of the Coast Mountain samples had *>500 m² road fill landslide presence*. Road fill landslide data is not available for the west coast of Vancouver Island. In southwestern Vancouver Island, 22 % of the samples had *>500 m² road fill landslide presence*.

No obvious differences in terrain attributes were evident to explain why road fill landslide likelihood was greater in southwestern Vancouver Island than in the Queen Charlotte Islands. The Queen Charlotte Islands study had greater clearcut landslide likelihoods than southwestern Vancouver Island, and the Queen Charlotte Islands are generally regarded as more unstable. It is possible that the differences in road fill landslide likelihoods were a result of different road construction practices.

Readers must use the results of this study carefully. The results are based on an apparently large sample of terrain polygons in southwestern Vancouver Island; however, this is actually a relatively small sample size, since the permutations of terrain attributes, such as bedrock, terrain categories, slope morphology, and slope gradient result in an extremely diverse range of slope conditions. It should not be assumed that all terrain types are represented in this study. As well, since the study area was relatively small it should not be immediately assumed that the results of this study necessarily apply to other areas within southwestern Vancouver Island.

Although the results of this study need to be carefully used, the consistent identification of specific terrain attributes as indicators of increased landslide likelihood, in this and other terrain attribute studies, shows that using terrain attributes to determine landslide likelihood is useful. While terrain attributes such as slope angle are well recognized in deterministic slope stability models, other terrain attributes such as slope morphology or soil drainage are either not recognized in deterministic models or are difficult to incorporate. In addition, deterministic models require intensive data input for accurate prediction of slope stability, a prohibitive requirement when assessing large tracts of land.

The terrain attribute statistical approach provides quantification of landslide likelihood, an improvement over qualitative assessments commonly used in forestry. The large tracts of land that must be assessed in forestry operations require methods that provide rapid yet accurate assessment of extensive areas. The use of terrain attributes provides a valuable approach for assessing landslide likelihood.

Table 8. Slope morphology and ***clearcut >500 m² landslide density*** in Coastal British Columbia

Study area	*Clearcut >500 m² landslide density (ls/ha)*	
	Single gullies and dissected slope morphology	**All other slope morphologies**
Queen Charlotte Islands[1]	0.29 – 0.51	0.02 – 0.18
West Coast Vancouver Island[2]	0.13 – 0.18	0.00 – 0.06
Coast Mountains[3]	0.00 – 0.02	0.00 – 0.06[3]
Southwestern Vancouver Island[4]	0.10 – 0.16[4]	0.02 – 0.06

1) Rollerson, 1992
2) Rollerson et al, 1998
3) Rollerson et al, 2001. Only benchy slope morphology ranked higher than gullied slope morphology, and it had only 11 samples.
4) Note that the southwestern Vancouver Island study used a weighted sample to derive landslide densities, while the other studies did not. The weighted samples result in slightly different average landslide densities.

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